THE USE OF VERY LOW FREQUENCY ACOUSTICS TO PROBE OCEAN BOTTOM PROPERTIES

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ABSTRACT

The possibility of using acoustics as a means of "probing" the properties of the ocean floor has been explored for numerous years. A particular aspect of this, namely, the use of very low frequency (VLF) seismoacoustic propagation to investigate sea-bottom properties, is explored in this paper. Generally, the propagation of sound in the sea is accompanied by some degree of interaction with the seafloor. In deep water, or for high frequencies, it is often sufficient to view the interaction as one of reflection or perhaps scattering of acoustic energy. However, in shallow water, or for very low frequencies, the seafloor may become an integral part of the propagation medium. As a result, the "acoustic waveguide" is no longer bounded by the sea surface and sea bottom, but extends to some depth (dependent upon frequency) into the bottom sediment and, possibly, basement level. Under these circumstances, the properties of the sea bottom and subbottom, particularly shear and compressional sound speeds and attenuations, are crucial determinants of the behavior of the sound propagation. Conversely, the characteristics of the propagation provide clues to the nature of the bottom material (geoacoustics). The preceding and other questions are being studied by the Naval Ocean Research and Development Activity (NORDA) as part of its long-term program in low-frequency acoustic propagation. Experiments have been conducted in several ocean environments using a vertical string of hydrophones in the water column and a number of ocean bottom seismometers on the seafloor. The response of these sensors to various sound sources - in particular, explosive shots, continuous wave (CW), airguns, and ambient noise - are used to deduce the geoacoustic properties of the environment. The role of seismic interface (Scholte/Stoneley) waves is demonstrated using both the measured data and results from a full-wave numerical modelling calculation. In addition, it is shown that sediment sound speed gradients and bottom attenuation play a significant role in determining the levels of refracted sound energy returning to the water column. The potential utility of ambient noise as an indicator of bottom properties is then briefly explored. Finally, conclusions are presented.

I. INTRODUCTION

For a variety of reasons ranging from purely economic considerations (e.g., oil prospecting) to acoustic surveillance, knowledge of the geophysical and geoacoustical properties of the seafloor is important to a broad community of investigators. Often, it is not the knowledge of these properties, per se, that is the ultimate goal, but rather the assessment of their influence in other areas. For example, it is well known that the properties of the sea bottom (and subbottom), particularly shear and compressional sound speeds and attenuations, strongly affect the behavior of low frequency sound propagation. Consequently, the characteristics of the sound provide, albeit indirectly, important information on the nature of the bottom material (geoacoustics).

Since direct methods of acquiring a detailed knowledge of bottom properties are both expensive and time consuming, if feasible at all, the possibility of using acoustics to probe the seafloor naturally suggests itself. A particular aspect of this problem, namely, the use of very low frequency (VLF) seismoacoustics to investigate seafloor properties, is the central focus of this paper. By "very low frequencies" we shall mean, here, frequencies below approximately 50 Hz, with particular emphasis on the regime below 20 Hz.

The VLF Program of the Naval Ocean Research and Development Activity

The results and methods discussed derive primarily from the long-term program in VLF acoustic propagation of the Naval Ocean Research and Development Activity (NORDA). As a result, a few words on NORDA's program are in order. The basic objective of NORDA's VLF program is the understanding of the propagation characteristics of VLF signals and ambient noise. Particular aspects include the following:

- Energy partitioning among the water, bottom, and subbottom propagation paths.
- Spectral characteristics of propagation along the paths.
- Spatial and temporal coherence of signals.
- Sound speed structure below the sea floor.
- The relative performance of hydrophones and geophones as VLF sensors.
- Modelling capabilities to predict VLF propagation in bottom-limited and shallow-water environments.

A typical experimental configuration is shown schematically in Figure 1. The environment was generally characterized by a sloping bottom, the nature of which varied from site to site; water depths ranged from 100 meters to several thousand meters. The sensors consisted of a vertical string of hydrophones (generally 16) and a distribution of several (as many as 15) ocean bottom seismometers (OBS). The hydrophones were spaced more closely than half-wavelength and spanned either the entire vertical extent of the water column, or a fraction of it. Each OBS consisted of a tri-axial set of

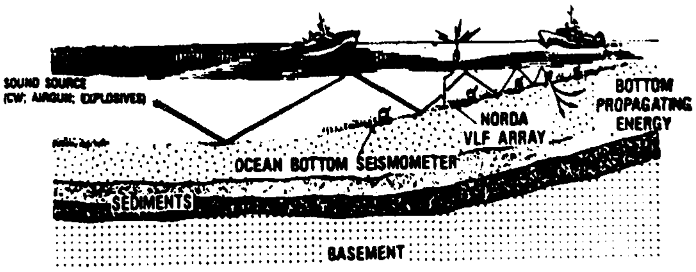

Figure 1. Configuration of a typical NORDA VLF experiment.

geophones and an external hydrophone. A continuous wave (CW) source (10 Hz and 15 Hz), airgun clusters, and explosives were used as sound sources. The CW source has the advantage of a repeatable output (source) level, easily obtained phase information (important for variability studies), and a continuous time response (allowing greater spectral resolution). On the other hand, separation of the multipath arrivals is not possible with a CW signal. The impulsive sources allow this separation and, in addition, provide broadband energy. The hydrophone signals were multiplexed and telemetered via UHF to a nearby ship, where they were converted from analog to digital signals. The OBS signals were recorded on the internal tape recorder and stored for subsequent playback and analysis. The results of the data analysis, coupled with the predictions of numerical models, were used to address the preceding questions.

The structure of the remainder of the paper is as follows. The Introduction is followed by a discussion of the salient points of acoustic propagation in the ocean, particular emphasis being placed on the role of the sea bottom. Included, is a brief exposition of particular mechanisms influencing the propagation: waveguide effects, seismic interface waves, ambient noise, and the effects of sound speed gradients in the bottom. Finally, conclusions are presented regarding the utility of VLF propagation as a tool for probing the seafloor.

II. CHARACTERISTICS OF LOW-FREQUENCY/SHALLOW-WATER SOUND PROPAGATION

A. Waveguide Effects

The propagation of sound in the sea is generally accompanied by some degree of interaction with the seafloor. The likelihood of bottom interaction is determined largely by the sound-speed profile, whereas the degree to which the signal is affected by the interaction is dependent upon signal frequency, signal-to-noise ratio, grazing angle, water depth, and bottom properties (particularly absorption coefficient and critical angle). Generally, a negative gradient in sound-speed profile (as in summer conditions) leads to a greater likelihood of bottom interaction and, hence, greater bottom losses.

As the water depth decreases, or equivalently, as the acoustic wavelength increases (frequency decreases), the degree of interaction with the sea bottom increases. In deep water, or for high frequencies, it is often sufficient to view the interaction as one of reflection or perhaps scattering of acoustic energy. In shallow water, or for VLF frequencies, the seafloor plays a far more significant role. It is well known that shallow-water propagation is characterized by a waveguide-like behavior. That is, propagation is confined or "trapped" by the acoustic waveguide bounded by the sea surface and sea bottom. With increasing acoustic wavelength (more precisely increasing ratio of wavelength to water depth), more and more acoustic energy is transferred into the bottom ("bottom loss") until, eventually, a frequency is reached below which there is little effective propagation in the water column. However, even below this "cutoff" frequency for waterborne energy, the bottom can be an important path for interface and other seismic waves. These interface waves provide not only a "new" propagation path but, by virtue of their bottom-dependent behavior, an opportunity to investigate the structure of the sea bottom. The knowledge of the existence and properties of these interface waves is hardly new, going back at least to Rayleigh. Moreover, seismologists and geophysicists are quite familiar with them as a source of "noise" to be eliminated from their data. From an acoustics viewpoint, however, the experimental investigation of interface waves is potentially very promising, albeit relatively recent. More is said about these in a subsequent section. In a very real sense then, at VLF frequencies the acoustic waveguide is not limited by the sea bottom, but extends to some depth (dependent upon frequency) into the bottom sediment and, possibly, basement level.

B. The Influence of Bottom-Type on the Modes of Propagation

The nature of the sound propagation in an ocean medium depends both on the bottom material and the angle of incidence of the energy. Energy may propagate either as trapped, discrete, normal modes in the water column or form part of the continuous spectrum in the bottom. The demarcation between discrete and continuous modes is based on the critical angle, $\theta_c = \cos^{-1}(c_w/c_b)$, of the bottom, which depends on the compressional phase velocity in the water column c_w, and the bulk wave speed in the bottom, c_b. For grazing angles (measured with respect to the horizontal) less than θ_c much of the incident energy (all, if the bottom is lossless) is reflected, resulting in the propagation of discrete modes. For grazing angles greater than the critical angle, significant transmission into the bottom occurs, giving rise to continuous modes which, because they decay much more rapidly than $r^{-1/2}$, are largely confined to the near wave field.

Naturally, the partitioning of energy between waterborne and bottom propagating energy depends on the relative values of c_w, and the compressional and shear bulk wave speeds in the bottom, c_p and c_s, respectively.

Soft Seabeds

For the case $c_p > c_w >> c_s$, which characterizes soft seabeds, such as unconsolidated sediments or sedimentary rock, significant acoustic energy is transferred from the acoustic waterborne modes to bulk shear waves in the bottom. Since there is no critical angle for shear in this case, this energy "leakage" occurs even for low grazing angles. The waterborne modes are now no longer strictly discrete modes, since as they propagate they decay exponentially with range. They are variously named leaky modes, pseudo-modes, quasi-discrete modes, or virtual modes. Some authors even refer to them as discrete modes. In any case, for low grazing angles these quasi-discrete modes dominate the propagation. As the grazing angle increases, both compressional and shear waves propagate in the sea bottom.

Hard Seabeds

In hard seabeds ($c_p > c_s > c_w$) energy loss into the bottom is less significant. In this case there are two critical angles: A critical angle for shear waves, θ_{cs}, and a critical angle for compressional waves, θ_{cp}; $\theta_{cs} < \theta_{cp}$ since $c_p > c_s$.

For grazing angles less than the shear critical angle, θ_{cs}, "total" reflection results in discrete, trapped mode propagation in the water column. For $\theta > \theta_{cs}$, some acoustic energy penetrates the seafloor and is coupled into a shear wave. Although the modes now properly belong to the continuous spectrum, a small leakage out of the waveguide (water column) has a small effect on the modes: this means that the waterborne propagation is quasi-discrete.

For even greater grazing angles $\theta > \theta_{cp}$, the acoustic energy is coupled into both shear and compressional waves in the bottom and forms part of the continuous spectrum.

C. Scholte Interface Waves

For either of the above types of seabed, the ability of the seafloor material to support shear waves allows for the existence of interface modes of propagation.

The role of interface waves in underwater acoustics has received considerable attention in recent years, since these waves serve as a propagation mechanism (of both signal and noise) and as a tool for probing the seismoacoustic properties of the seabed. (See e.g., Rauch (1980)[1], Essen (1981)[2], Schmalfeldt (1983)[3], Ali (1984, 1987)[4,5], etc). These waves, also called surface waves, are characterized by amplitudes which decay exponentially away form the interface between a solid and another medium. Hence, they are effectively restricted to the immediate vicinity of the interface.

Since they are a combination of compressional and shear body waves, at least one of the interfaces must be a solid for interface waves to exist. The other medium can be vacuum, liquid, or solid, in which case the corresponding interface wave is denoted a Rayleigh wave, Scholte wave, or a Stoneley wave, respectively. At limiting frequencies the distinction between lowest-order Rayleigh and Scholte waves becomes somewhat arbitrary. In particular, consider the case of propagation in a three-layered medium: vacuum over liquid (thickness h) over a solid half-space. For large wavelengths ($h/\lambda \rightarrow 0$), the liquid layer acts as an insignificantly thin film - i.e., the large wavelength propagation does not "see" the liquid layer. In this case, the phase and group velocities of the lowest mode Scholte interface wave tend to the Rayleigh wave velocity in the solid half-space. On the other hand, for very small wavelengths ($h/\lambda \rightarrow \infty$) the liquid layer is effectively very thick and the lowest mode interface wave propagates as a Scholte wave at the interface between the liquid and solid.

The speeds of interface waves (phase velocities) are always less than the sound speed in the water column and the shear speed in the bottom. In the ideal case of two homogeneous half-spaces in contact, Scholte waves are non-dispersive. Moreover, for unconsolidated sediments (clay, silt, sand) with relatively low shear speeds the Scholte wave speed, c_{sch}, and attenuation, α_{sch}, are close, respectively, to the bulk shear wave speed and attenuation, c_s and α_s. In particular, $c_{sch} \approx 0.9c_s$ and $\alpha_{sch} \approx 1.1\,\alpha_s$. In realistic media, particularly layered seabeds, the propagation speeds are dependent upon the frequency - that is, the propagation is dispersive. The dispersion properties of Scholte waves allow one to obtain information on the properties of the seabed sediments, at least to a depth of one or two Scholte wavelengths. In particular, measured dispersion curves coupled with appropriate numerical results (e.g., synthetic seismograms and dispersion curves) make it possible to determine the shear speed and shear attenuation profiles. It should be noted that the shear properties are of far greater interest than the compressional wave properties since the latter have a negligible effect on Scholte wave propagation.

As noted earlier, interface wave amplitudes decay exponentially away from the interface. As a result, effective direct excitation of Scholte waves requires a source close (of the order of one wavelength) to the interface. At VLF frequencies, particularly below acoustic cutoff, this condition is normally satisfied. As a result, both waterborne sources and wind/wave action at the water surface can lead to the excitation of Scholte waves and hence to the propagation of acoustic energy, including ambient noise, in the seabed and the water column, even at frequencies below the acoustic waveguide cutoff.

Depending on the particular geoacoustic environment, the effects of Scholte waves may extend over a significant vertical portion of the water column (Brooke, 1985[6]; Rauch, 1985[7]). The penetration depth into the seabed of Scholte waves is approximately equal to the Scholte wavelength, which is less than the corresponding water wavelength. Because of the very small attenuation in the water column, however, the penetration of the Scholte wave into the water column may greatly exceed this value. Thus, hydrophones may show the effects of Scholte waves over a significant part of the water column, particularly for high speed (hard) bottoms (for which most of the Scholte wave energy is in the water).

An example of the effect on propagation of interface waves (via the inclusion of shear) is show in Fig. 2, which was calculated using the SAFARI Fast Field Program (FFP) numerical model. The environment is a 100 m depth isospeed (1500 m/s) duct, with the following properties: compressional speeds of 1750 m/s, shear speed of 500 m/s, compressional attenuation of 0.1 dB/λ_p, shear attenuation of 0.2 dB/λ_s, and a density ratio between bottom and water of 2.0. The source is placed just above the bottom (95m depth) and the receiver is on the bottom. Since the source frequency (5 Hz) is below the cutoff frequency for discrete modes (approximately 10 Hz in this case), one would not expect any significant waterborne propagation in this case. This is confirmed by Fig. 2 (b), which shows the propagating energy vs. wave number (i.e., the FFP integrand, which is related to the Green's function). There are no discrete modes and only one highly damped virtual or "leaky" mode. As already noted, continuous (or virtual or leaky) modes correspond to steep propagation angles above the critical angle (here, 33.6°); hence they result in significant transmission into the bottom. However, because they decay much more rapidly than $r^{-1/2}$ they are confined largely to the near field. Thus, in this case, the only viable propagation mechanism is that associated with the evanescent mode, seen as the prominent response at 0.6 m^{-1} wave number, which turns out to be a Scholte interface wave. This is illustrated in Fig. 2 (a), which shows the propagation loss vs. range. If the interface wave is excluded (no shear case) the propagation is very poor, since energy is carried only by the highly attenuated continuous mode. With shear included, the propagation does show some interference with the continuous mode at short ranges, but at longer ranges only the interface mode remains. It is noted that the propagation speed of the Scholte wave is here about 443 m/s. This is consistent with the approximation (valid for a nondispersive environment) that the Scholte propagation speed is about 0.9 of the sediment shear speed.

Thus, for very low frequency acoustic propagation, the effect of shear is to enhance propagation. It should be noted, however, that at higher frequencies (above cutoff) shear increases the propagation losses for waterborne propagation, and thereby degrades propagation.

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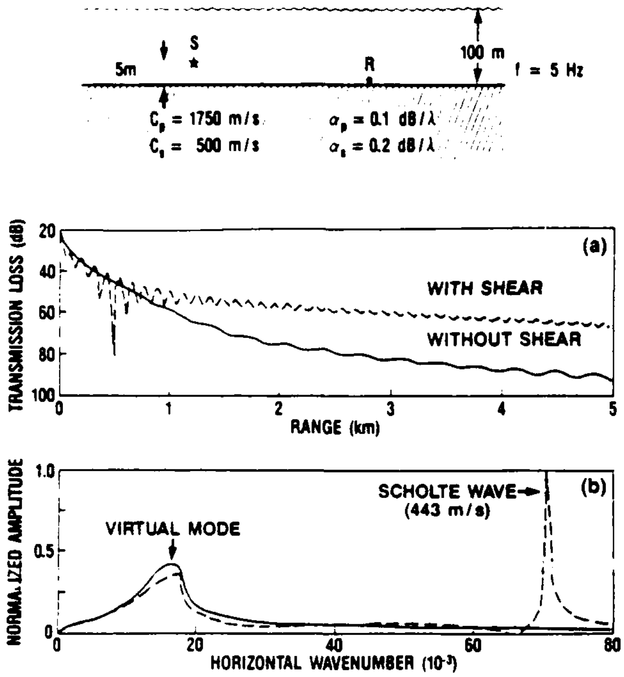

Figure 2. The effect of shear (Scholte waves): (a) transmission loss and (b) wave number spectrum (FPP Integrand).

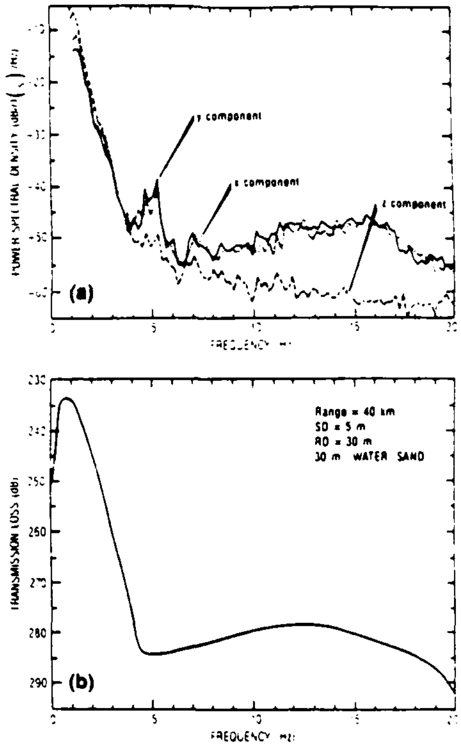

Figure 3. Comparison of (a) experimental seafloor seismic ambient noise (Mediterranean) and (b) the theoretical Scholte wave response.

It has already been pointed out that Scholte waves are an effective carrier of ambient noise. Indeed, a considerable portion of infrasonic ambient noise (waterborne and seismic) appears to consist of Scholte waves. The plausibility of this result is suggested by Fig. 3, which compares the seismic noise measured with a tri-axial geophone with the response predicted (using SAFARI) for Scholte wave propagation. The figure clearly suggests that the seismic ambient noise has a behavior that is characteristic of interface wave propagation (the region below about 6 Hz in the theoretical result) and not of waterborne propagation.

An example of recently measured acoustic ambient noise levels is shown in Fig. 4, which provides spectral levels over a period of 1.5 hours. The measurement was made in shallow water (depth 125 m) in the Gulf of Mexico, off the coast of Louisiana, using a vertical string of hydrophones. The result in Fig. 4 was obtained from the deepest hydrophone (110 m). The steep drop-off in level between 2 or 3 Hz and 10 Hz is quite evident.

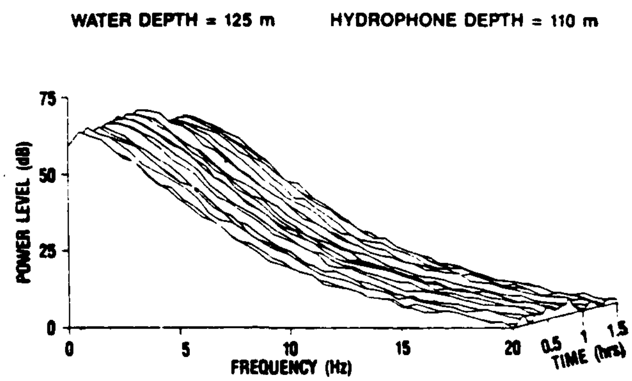

Figure 4. An example of acoustic ambient noise (Gulf of Mexico).

D. The Effects of Refracting Sediments in Range-Dependent Seafloors

As already mentioned, the propagation of sound, particularly at low frequencies, is strongly determined by sound speed gradients in the bottom. Fig. 5 provides a quantitative demonstration of this effect, using parabolic equation (PE) numerical models. The PE model is used in this case since it is designed to handle propagation in range-dependent environments (but cannot handle shear wave propagation in the bottom), whereas SAFARI, for example, handles only horizontally stratified environments (but does treat shear waves). The problem represented in Fig. 5 is that of upslope-propagation of acoustic energy. A time harmonic (CW) point sound source of 25 Hz is placed at a starting range ($r = 0$) and a depth below the ocean surface of 112 m (i.e., $z_s = 112$ m). The transmission loss as the energy propagates upslope is represented by contour levels; the black line represents the ocean bottom. Clearly, as the sound propagates from deep to shallow water the energy decreases from its maximum level near the sound source to lower levels in the water and in the bottom. For Fig. 5(a) the sound speed in the water column is a constant $c_w = 1500$ m/s, the speed in the sediment is a constant $c_b = 1704.5$ m/s, the attenuation is $\alpha = 0.5$dB/λ, and the density is $\rho = 1.15$ g/cm^3. This problem is often referred to as the Jensen-Kuperman problem (1980)[8]. For the conditions of this problem, three trapped (discrete) modes exist at the starting, deep portion (200 m) of the range. It turns out that the source depth (z_s = 112 m) is a node point of mode 2; therefore only modes 1 and 3 are excited at this source depth.

The increasing grazing angle of the sound "ray", with increasing distances up the slope, eventually results in sizable penetration into the slope at the critical angle of the bottom. In other words, at the critical angle acoustic energy is converted from the discrete, trapped spectrum into the continuous spectrum. The point in range at which this conversion occurs for the ray corresponds to the cutoff depth of the equivalent mode (Jensen and Kuperman, 1980). Mode 3 cutoff occurs near r = 7 km, as is strikingly evidenced by the tongue-like beam penetrating into the sediment. Mode 1 (with a lower grazing angle) continues to propagate beyond the top of the slope. At ranges less than approximately 7 km, an interference pattern between modes 1 and 3 is evident.

Next, we consider the case in which the attenuation is zero (α = 0) and, instead of an isospeed sediment, the sound speed gradient, g, is 0.85 s^{-1}. In contrast to the case g = 0, there are four trapped modes present at 25 Hz for d = 200 m. Once again, the highest mode cuts off near r = 7 km. However, the others persist to the top of the incline. A contour plot of transmission loss for a 25 Hz source appears in Fig. 5(b). The downward-propagating beam appearing for g = 0 has been replaced by a horizontally propagating beam near z = 250 m. It is seen that the signal at the top of the slope is a few decibels stronger for the refracting bottom. Finally, we consider the realistic case in which both attenuation and a bottom gradient are present. Figure 5(c) illustrates the result for = 0.5 dB/λ and g = 0.85 s^{-1}. In this case, we see that the levels towards the top of the slope are reduced, compared with the refracting, lossless bottom (Fig. 5(b)).

We summarize with the following remarks. For upslope propagation, energy penetration into the sediment increases with range. However, a positive sound speed gradient in the sediment prevents deep penetration of this energy, and returns some of it to the water. If attenuation is small in the upper sediment layer, energy that penetrates into the bottom is refracted back into the water column with little loss. One might expect this effect to enhance propagation far up the slope. If attenuation is large in the upper sediment layer, much less energy is returned to the water since rays are attenuated in addition to being refracted in the sediment. Thus, one would expect signals received near the top of the slope to be weak in this case. Additional details are provided in Collins et al (1988)[9].

E. Example of Propagation in a Horizontally Stratified Environment

Even in the absence of bottom gradients, significant propagation effects can take place. We consider the results of a SAFARI simulation of propagation measurements made off Cape Fear, North Carolina. The geoacoustic input parameters are shown in Fig. 6(a). Although based on the Cape Fear environment (CTD casts and seismic-derived formation velocities), the parameters are nevertheless a simplification. In particular: gradients in the bottom are not accounted for, the shear values are estimates, and the water depth is assumed to be a constant 400 m (the water depth at the location of the hydrophone string). The result of a pulse calculation using SAFARI is shown in Fig. 6(b). The pulse, with a peak amplitude at 10 Hz and a depth of 85 m, was designed to simulate the response of the explosives used in the experiment. The response with range is plotted against time reduced by 4.3 km/s, the speed of the deepest layer in the model (Figure 6(a)). The waterborne arrivals are clearly dominant, separating with range into 3 or 4 discrete modes. Preceding the water arrivals, the head waves along the various bottom layers are evident, albeit with reduced

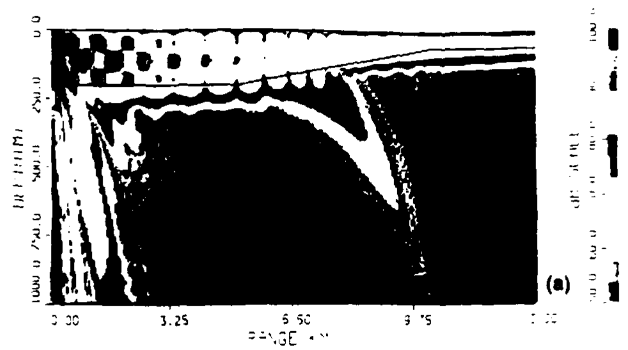

Figure 5(a). Upslope acoustic propagation: g = 0; α= 0.5 dB/λ .

Figure 5(b). Upslope acoustic propagation: g = 0.85/s; α= 0.

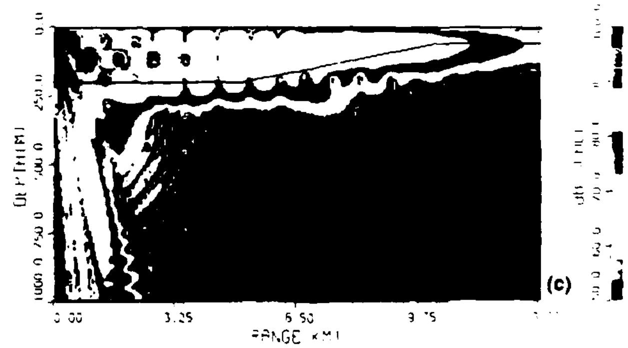

Figure 5(c). Upslope acoustic propagation: g = 0.85/s; α= 0.5 dB/λ .

amplitudes. For source and receivers closer to the bottom than shown here, the model predicts another dominant mode, a Scholte interface wave propagating with a velocity of approximately 523 m/s. This is seen in Fig. 6(c), the SAFARI result for a 10 Hz CW sound source. Apart from the Scholte mode, the three trapped modes and the higher-speed continuous modes are also evident. The transmission loss curve demonstrates that the propagation is dominated by the trapped modes, except in the near field where the Scholte wave is significant.

F. Ambient Noise

The ambient noise field is often regarded as an unwanted part of the propagation. In fact, however, it does offer the possibility of deducing information on the bottom properties, particularly in shallow water. This is not surprising, since the propagation of ambient noise, no less than that of acoustic signal, is influenced by the sea bottom and the sound

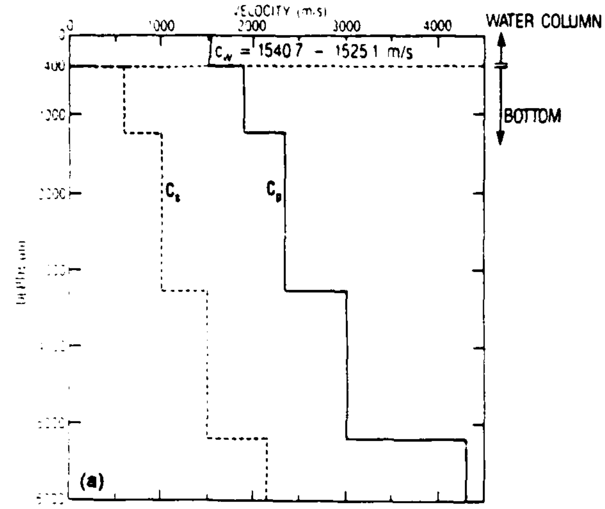

Figure 6(a). Geoacoustic input parameters for Safari Model (Cape Fear).

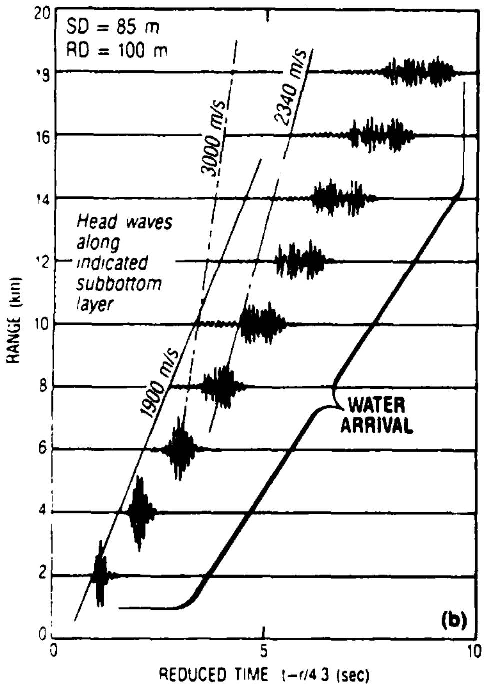

Figure 6(b). Result of a Safari pulse calculation for a simplified Cape Fear environment.

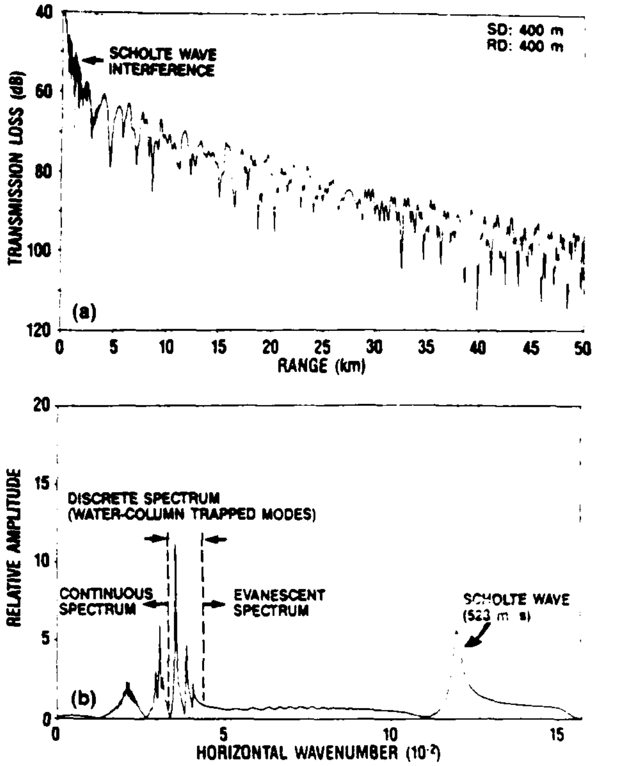

Figure 6(c). Typical Safari results for CW (10 Hz) for Cape Fear: (a) transmission loss and (b) wave number spectrum (FFP Integrand).

speed profile in the water column. Conversely, appropriate measurements of ambient noise can lead to information on these environmental parameters and also on the source mechanisms.

In the past, the need to understand ambient noise was particularly evident in the areas of signal processing, since the noise characteristics--particularly spatial and temporal coherences--set fundamental limits on array gains and signal/noise separation. More recently, an awareness of the significant role of ambient noise in ultra low (< 1 Hz) frequency (ULF) and VLF propagation has led to increased interest in the subject (see references 10 and 11, for example).

In shallow water, both nearby and distant noise sources can be significant. The former may arise from wind/wave action, while the latter are often attributable to distant shipping. The noise from distant sources will most likely arrive in the form of normal (discrete) modes confined to a small angle about the horizontal direction. This can be explained by the fact that energy propagating at steep angles will not survive the attenuation implicit in repeated bottom and surface interactions over long ranges. Buckingham (1987)[12] has shown that the vertical directionality of the ambient noise in shallow water permits the determination of the critical angle of the bottom (in the absence of strong interference from local shipping).

The nearby sources will contribute via the direct path. The direct path propagation, as well as energy arising from bottom interaction at angles steeper than critical, gives rise to the continuous modes referred to earlier. Thus the continuous modes contribute to the vertically propagating noise field.

To properly understand ambient noise behavior an appreciation of the significance of propagation is essential. In particular, in using measured data to determine the actual source spectrum level of the noise sources, it is necessary to account for the propagation effects. For example, in assessing the noise sources in a VLF shallow-water environment the ocean waveguide effect must be "subtracted". Without this correction, the comparison of noise source levels from data obtained in different environments can lead to erroneous conclusions. On the other hand, the apparently large spread in reported ambient noise levels from various geographical test sites becomes considerably reduced once the propagation effects are accounted for (Schmidt, 1988)[13].

CONCLUSIONS

The propagation of VLF sound, particularly in shallow-water environments, is strongly affected by the geoacoustic properties of the ocean bottom. As a result, the "inverse" process, viz., the determination of bottom properties from the behavior of the sound, is not only feasible, but often the only practical procedure.

Depending on the circumstances, a significant fraction of waterborne VLF energy may be transferred into the seabed, in the form of interface and other seismic waves. Apart from providing an effective propagation path for acoustic energy, these interface waves allow one to obtain information on the properties of the seabed, at least to a depth of one or two Scholte wavelengths. These deduced properties include the shear sound speed profile and bottom attenuation. Numerical Modelling, using both range-dependent parabolic equation models and full-wave FFP models, coupled with measured data, provides considerable insight into the propagation modes and hence the bottom geoacoustics. In this regard, analysis of dispersion curves and stacked seismograms are particularly informative. Even infrasonic ambient noise carries with it evidence of its interaction with the seabed. Clearly, the propagation of very low frequency sound provides an eminently useful tool for probing the geoacoustic properties of the ocean floor.

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